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Assorted studies have been conducted with buoyancy driven flow of a rotating fluid. The results have numerous applications to physical oceanography. Studies of convection were initiated in 1990 with observations of motion driven by surface cooling over a limited area in a rotating fluid (Whitehead 1991). The subsequent studies were then split into two separate experiments involving convection in the two types of configurations which are likely to produce the very coldest water in the oceans, one being over a continental shelf (Whitehead, 1993 and Whitehead and Kimura 1994) and the other being with deep convection in a stratified rotating fluid (with Whitehead Marshall and Hufford 1996). In all these studies, algebraic formulae have been isolated which express the rates of buoyancy flux, the associated density difference of the cooled water, and the accompanying velocity and length scales. Such formulae were tested by the experiments over as wide a range of variables as possible, and always in a range of importance to convection in the ocean. The results give theoretical constraints (backed by physical laboratory evidence) concerning the expected rates of dense water formation. They are useful in planning field experiments and testing oceanic observations of actual dense water accumulation.

In "A Laboratory Model of Cooling over the Continental Shelf" (Whitehead 1993) A laboratory experiment was conducted where hot water is cooled by exposure to air in a cylindrical rotating tank with a flat shallow outer "continental shelf" region next to a sloping "continental slope" bottom and a flat "deep ocean" center. It is taken to be a model of wintertime cooling over a continental shelf. The flow on the shelf consists of cellular convection cells descending from the top cooled surface into a region with very complicated baroclinic eddies. Extremely pronounced fronts are found at the shelf break and over the slope. Associated with these are sizable geostrophic currents along the shelf and over shelf break contours. Eddies are particularly energetic there. Cooling rate of the hot water is determined and compared with temperature difference between "continental shelf" and "deep ocean". The results are compared with scaling arguments to produce an empirical best fit formula that agrees with the experiment over a wide range of experimental parameters. A relatively straight trend of the data causes a good collapse to a regression line for all experiments. These experiments have the same range of governing dimensionless numbers as actual ocean continental shelves in some Arctic regions. Therefore this formula can be used to estimate how much temperature decrease between shelf and offshore will be produced by a given cooling rate by wintertime cooling over continental shelves. The formula is also generalized to include brine rejection by ice formation. It is found that for a given ocean cooling rate, shelf water will be made denser by brine rejection than by thermal contraction. Estimates of water density increase implied by these formulas are useful to determine optimum conditions for deep water formation in polar regions. For instance, shelves longer than the length scale $0.09\ f\ W^{5/3}/B^{1/3}$ (where f is the Coriolis parameter, W is shelf width and B is buoyancy flux) will produce denser water than shorter shelves. In all cases, effects of Earth rotation are very important, and the water will be much denser than if the fluid were not rotating.

In "Localized convection in rotating stratified fluid", (Whitehead, Marshall and Hufford 1996), we have found that the deepening of the mixed layer from cooling over stratified rotating fluid stops becoming one-dimensional after a few rotations. Then baroclinic eddy pairs are observed. These transport the deepened mixed layer water laterally so that the mixed layer under the cooled region ceases its deepening. In this way, the sideways removal of the cooled water limits the temperature of deep water formed for any one cooling event. Formulas for the final mixed layer depth developed by John Marshall and colleagues are dramatically verified by the data obtained in this experiment. We hope that this will allow us to estimate the volume of water that can be cooled each winter and what its new density will be. The results are in a stage where they can be tested against actual ocean observations to see if they realistically predict the changes in water mass, speeds of currents and so forth.

Application of exchange flow dynamics to Fram Strait (with Hunkins1992) produced predictions of the expected salinity and depth of the upper (low salinity) layer of the Arctic Ocean given fresh water sources in the region. The results produced reasonable agreement between the predictions and oceanic measurements. Laboratory experiments and theory were conducted to observe the flow patterns and transport in density driven rotating experiments. In all experiments, there was a layer of deep salty water over which the dynamically active shallow layers were placed. In "dam break" experiments water with one density flows into a second basin after a sliding gate is removed. Water of a second density flows back into the first basin. The size and location of the currents for various values of density difference, rotation rate, and assorted sidewall geometries was recorded. Volume flux of the fluid was also measured and compared with a theory for lock- exchange flow of a rotating fluid. In experiments with a passive upper layer, easterly winds (like those in the Arctic Ocean) drive the upper level water into the arctic ocean and therefore oppose the buoyant exchange. Westerly winds would drive the water out of the Arctic ocean. This indicates that the exchange between the arctic ocean and the Greenland-Norwegian sea is likely to be buoyancy driven rather than wind driven. Crude estimates of the volumetric and fresh water exchange rate from the lock- exchange formulas are compared to observed ocean fluxes and approximate agreement is found.

A variety of experiments have been conducted involving a tank of rotating thermally stratified water subjected to temperature differences along the top or sidewalls of the tank (with Bulgakov and Korotaev, 1996a,b, 1997 and with Pedlosky and Veitch 1997). This produced circulation whose strength and structure can be compared with a theoretical model extended from formalisms developed by Barcilon and Pedlosky thirty years ago. In this problem, the explicit role of boundary layers and their contribution to circulation in the interior fluid is quantified as a function of two dimensionless numbers. The most striking, and as far as we know, unanticipated prediction is that circulation was cyclonic at some depths and anticyclonic at others. For deep inland seas such as the Black Sea, and possibly the Arctic Ocean a deep circulation with both signs is expected to be uncoupled from the wind- driven surface flows. The dynamical origins of such deep circulation have only recently been appreciated. Our recent experiments also help us to quantify the role of the boundary layers in pumping water into stratified fluid under such conditions. There are a variety of such boundary layers with different thicknesses. Many have now been verified by our laboratory measurements. In some cases, the circulation in such containers has both signs but both signs may not have the same magnitude. Applications in marginal seas or lakes seem obvious, but no examples of adequate observations are known. Circulation in marginal seas such as Black Sea, the Caribbean or the Japan sea is scantily understood, but we continue to look for a basin as a potential site of a deep circulation study. There is some hydrographic evidence for a counter cyclonic current at 1500 m in the Black Sea,

which is in accordance with some of our early laboratory studies. Existing oceanographic literature apparently does not contain observations of sufficient quality to reveal circulation deep in either the Arctic ocean or the Caribbean sea.

Two experimental studies of flow separation have been conducted. One involved a flow of uniform density along a wall. We found that the current veers sharply offshore at some distance downstream from the source. The important dynamics which governs separation of flows from a coast are still poorly understood, and some theories which agree with the experment (Stern, Chassignet and Whitehead 1997) imply that the shear distribution is responsible for the separation. The criterion governing separation was quantified by reducing the trajectories of many runs to a cluster of results depending on two dimensionless numbers, the Ekman number and a dimensionless volume flux divided by Ekman number to the 1/3 power. Mechanisms of the separation by eddy dipoles have been developed by Stern and Chassignet. The results strongly imply that those who seek to predict coastal current behavior should monitor the vorticity distribution carefully. In a second experimental study of flow separation, the formation of a gyre upstream of a rotating flow over a weir was found. (Borenas and Whitehead 1997). Favorable comparison with calculations by K. Borenas were made. The results have implications for locating current meters in the vicinity of weir flows in the ocean.

Following a review of multiple state studies (Whitehead 1995b), some laboratory experiments have successfully produced the theoretically predicted multiple states from thermal and salinity forcing. There is a simple explanation as to why density in marginal seas and estuarine regions are usually dominated by salinity differences rather than temperature differences whereas the large ocean is temperature dominated. Quantifiable criteria have been isolated (Whitehead 1996,7) whick show that the answer is not only because the marginal regions receive proportionally more fresh water as is commonly supposed but that there are important dimensionless numbers relating time scales of temperature and salinity which govern the behavior. Catastrophic transitions from salinity to thermally driven cells in estuaries and shelves are possible. Possible examples are being sought. It is not generally appreciated that the combination of wind stress and convection also can have multiple states. Work continues in this important problem.

The important role of interial critical control of rotating fluid in the oceans continues to be a common feature of many of the studies (Hunkins andWhitehead 1992, Wilber et al 1993, Whitehead and Kimura 1994, Whitehead 1997a, Borenas and Whitehead1997). The laboratory studies are still the only way to determine such flows, numerical models have yet to incorporate the proper dynamics. The 1997 SummerSchool in Geophysical Fluid Dynamics will study such phenomina for a variety of applications in the oceans, atmosphere, and elsewhere. In conjunction with Larry Pratt, who is the principal lecturer of the summer school, the Principal Investigator intends to write a book on these important nonlinear problems for rotating fluids.

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